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LETTER TO THE EDITOR

Elastic and inelastic scattering of 40 eV electrons from atomic lead

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Abstract. Differential and integral electron impact cross sections for elastic scattering and for the excitation of the first five states in lead have been determined at 40 eV impact energy. The cross section measurements were placed on the absolute scale by normalizing to the optical *f*-value of the 6p7s $^3P_1$ transition which is the upper state for the 7229 Å, 4057 Å and 3639 Å laser emissions. The integral cross sections for elastic scattering (6p^2 $^3P_0$) and for the excitation of the 6p^2 $^3P_1$, 6p^2 $^3P_2$, 6p^2 $^1D_2$, and 6p7s $^3P_0$ (+6p7s $^3P_1$) states are: 44, 0·15, 1·5, 0·05 and $8{\cdot}4\times10^{-16}$ cm^2 respectively.

Optical absorption spectra of lead was obtained by Grotrian (1923). Only the 2833 Å transition from the ground state was observed in our region of interest (0 to 4·4 eV). Recently, large optical amplification and super-radiance for the 7229 Å transition has been found in pulsed discharges of lead vapour (Fowles and Silfvast 1965, Silfvast and Deech 1967, Isaev and Petrash 1969, Chen 1975). Silfvast and Deech (1967) reported a gain of 63 dB in 10 cm effective length. The 4057 Å and 3639 Å emissions have been observed by Isaev and Petrash (1969). To our knowledge, no experimental measurements or theoretical calculations on the electron scattering of atomic lead exists. Here we present normalized differential and integral cross sections for elastic scattering and for the excitation of the first five electronic states in lead at 40 eV. A typical electron impact spectrum is shown in figure 1.

The differential cross section for elastic scattering has minima at 40° and 90° scattering angles (see figure 2). These minima are similar to those seen in the elastic scattering from other elements with high Z numbers. With the exception of the $^1D_2$, all cross sections show forward peaking and the 6p^2 $^3P_2$ excitation and the 6p7s $^3P_{0,1}$ (unresolved) possess distinct minima at around 90°. The 6p^2 $^1S_0$ excitation was only detected at 80° and above.

The predominant line seen in pulsed discharges of lead vapour is at 7229 Å. An examination of table 1 indicates a population inversion can be well achieved by 40 eV electrons for the 6p7s $^3P_1 \rightarrow$ 6p^2 $^1D_2$ (7229 Å) transition. For the 6p7s $^3P_1 \rightarrow$ 6p^2 $^3P_1$ (3639 Å) and for the 6p7s $^3P_1 \rightarrow$ 6p^2 $^3P_2$ (4057Å) transitions, the upper to lower level cross section ratios are much smaller, (56 : 1) and (5·6 : 1) respectively. The measurements will have to be extended to other impact energies in order to make general conclusions about the Pb laser transitions.

The electron impact spectrometer is similar to the one described earlier (Williams and Trajmar 1974). An atomic Pb beam was generated by heating a tantalum crucible

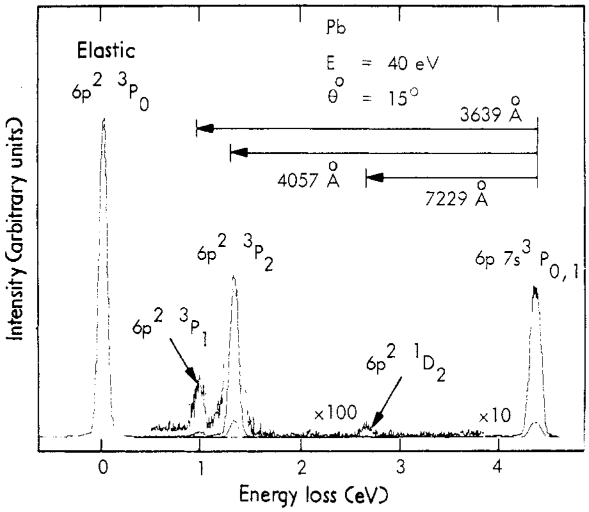

Figure. 1. Energy-loss spectrum of Pb at 40 eV impact energy and 15° scattering angle.

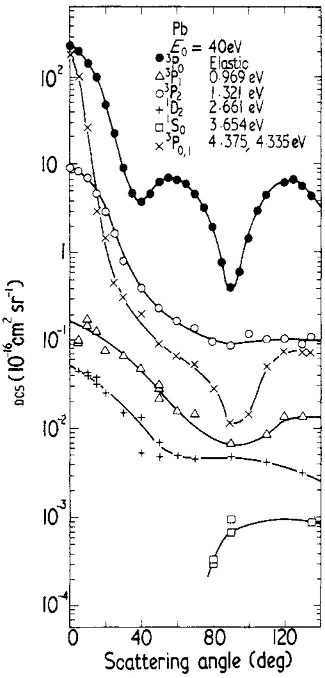

Figure 2. Differential cross sections for elastic and inelastic scattering from Pb at 40 eV.

Table 1. Summary of integral cross sections (10^{-16} cm^2) for $E_0 = 40$ eV

Elastic	$6p^2\ ^3P_1$	$6p^2\ ^3P_2$	$6p^2\ ^1D_2$	$6p7s\ ^3P_{0,1}$
44·0	0·15	1·5	0·050	8·4

containing Pb by electron bombardment. The Pb beam was crossed at right angles by an energy selected electron beam. The electron scattering intensities at $E_0 = 40$ eV and at various scattering angles (θ) were determined as a function of energy loss using pulse counting by multi-channel scaling techniques. The impact energy scale is accurate to $\pm 0{\cdot}5$ eV and the angular resolution is estimated to be between 1·7° and 3·2°.

The elastic scattering angular dependence in the 10° to 140° range was measured in a time short compared to the instrumental drift. Several measurements verified the consistency of the elastic scattering intensity distribution. An effective path length correction for our scattering geometry converted the elastic intensities to differential cross sections (DCS) in arbitrary units. The effective path length correction factors were estimated on the basis of measurements carried out with a similar instrument. (In these measurements the elastic electron scattering angular distribution was measured for He, and from the combination of these intensities and the known cross sections, the effective path length correction factors were obtained.)

Ratios of the inelastic scattering intensities to the elastic intensity were determined from each spectrum taken at fixed angles in the 10° to 140° range. Products of these ratios and the elastic DCS yielded DCS's for inelastic transitions in the same arbitrary units. Below 10° the elastic intensity has a sizable contribution from the direct beam; therefore, a low angle calibration based on the intensity distribution of the 6p7s $^3P_{0,1}$ excitation from 0° to 30° was performed with an effective path length correction. The DCS's obtained were normalized to those obtained from the elastic ratio data by matching the two curves in the overlapping angular region. From ratios of other inelastic intensities to the 6p7s $^3P_{0,1}$ transition at low angles and the 6p7s DCS at low angles, the DCS's of other inelastic transitions were obtained in this angular region.

All cross sections were normalized to the absolute scale by using the optical f-value for the 6p7s $^3P_1$ transition. An f-value of 0·25 was used based on the experiments of Bell and King (1961) and the calculated optical transition probabilities of Lawrance (1967). The generalized oscillator strength is defined by Bethe (1930) as:

$$f_{0n} = \frac{W}{2}\frac{K_0}{K_n}(\Delta P)^2 \, \mathrm{DCS}_{0n}(\theta)$$

where W is the excitation energy, K_0 and K_n are the colliding electron momenta before and after collision respectively. ΔP is the change in momentum. It has been shown by Lassettre *et al* (1969) that the value of the generalized oscillator strength at zero momentum transfer is equal to the optical f-value whether the Born approximation holds or not. Therefore, a plot of the generalized oscillator strength for the 6p7s $^3P_{0,1}$ level as a function of ΔP^2 was made and extrapolated to zero momentum transfer. The instrumental resolution did not permit a separation of the 6p7s $^3P_0$ and $^3P_1$ states. The contribution of the $^3P_0$ level to the unresolved composite is believed small at low scattering angles and the optical f-value for this transition is zero. Therefore, extrapolation of the composite $^3P_{0,1}$ generalized oscillator strength to zero momentum transfer gives the optical f-value of the $^3P_1$ state. The extrapolated value was normalized to the optical f-value and the factor so obtained normalized all cross sections to the absolute scale. The normalized generalized oscillator strengths and the method of extrapolation is shown in figure 3. All cross sections were extrapolated to 0° and 180° and then integrated to obtain integral cross sections (table 1). The cross sections are believed accurate to $\pm 20\%$ relative to each other, while the absolute values are believed accurate to within a factor of 2. These cross sections can be easily renormalized when more

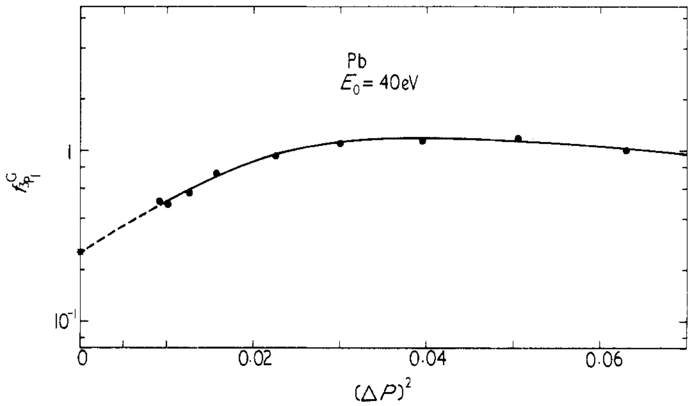

Figure 3. Normalized generalized oscillator strengths for the 6p7s $^3P_{0,1}$ state as a function of ΔP^2. The optical oscillator strength of Bell and King (1961) (*) is shown at $\Delta P^2 = 0$.

accurate elastic absolute measurements become available or when reliable theoretical calculations are completed.

The $6p^2\ ^3P_0 \rightarrow 6p^2\ ^1S_0$ transition constitutes another example of vanishing cross sections. It has been shown using group theoretical arguments (Goddard *et al* 1971) that $P_g \rightleftarrows S_g$ transitions should have zero amplitude for electron impact excitation at 0° and 180°. Indeed, we have not been able to detect scattered signal at low scattering angles corresponding to this transition.

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References

Bell G D and King R B 1961 *Astrophys. J.* **133** 718
Bethe H A 1930 *Ann. Phys., Lpz.* **5** 325
Chen Che Jen 1975 *Appl. Phys. Lett.* in the press
Fowles G R and Silfvast W T 1965 *Appl. Phys. Lett.* **6** 236
Goddard W A III, Huestis D L, Cartwright D C and Trajmar S 1971 *Chem. Phys. Lett.* **11** 329
Grotrian W 1923 *Z. Phys.* **18** 169
Isaev A A and Petrash G G 1969 *JETP Lett.* **10** 119
Lassettre E N, Skerbele A and Dillon M A 1969 *J. Chem. Phys.* **50** 1829
Lawrance G M 1967 *Astrophys. J.* **148** 261
Silfvast W T and Deech J S 1967 *Appl. Phys. Lett.* **11** 97
Williams W and Trajmar S 1974 *Phys. Rev. Lett.* **33** 187